Superposition of Effects in Calculating the Deterioration of Tubular Structures and in Non-newtonian Fluid Flow

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The paper outlines the superposition of effects by resorting to the principle of critical energy in both tubular structures as well as in non-Newtonian fluid flow. A relation is proposed for the calculation of critical stress in a cracked specimen, by considering the concept of deterioration; - one determines the amount of deterioration caused to tubular specimens under static loading, depending on the crack geometry and position; - relationships have been proposed for calculating deterioration by considering the crack depth and length. Considerations refer to specimens under one single load (axial force or bending moment) as well as specimens under two simultaneous loads (axial force and bending moment). We put forth a relation for the superposition of the Couette flow effects and the Poiseuille pressure flow effects of a non-Newtonian fluid. The theoretical results have been accounted for by experimental data.

Keywords: deterioration; superposition of effects, tubular structures, cracks, non-Newtonian fluid flow

The superposition of effects when a solid or fluid body with nonlinear behaviour is under load can be currently solved by using the principle of critical energy [1 ÷ 3]. This principle has been used to solve many engineering problems involving the superposition of effects [3 ÷ 10].

Further down, one has applied the principle of critical energy to solving two issues that involve the superposition of effects; the former refers to solid bodies and the latter to fluid bodies. Relationships have been established for calculating deterioration to tubular structures under two simultaneous different loads and a proposal is made for the calculation of the pressure gradient in the case of the superposition of the Couette driving flow and the Poiseuille pressure flow.

Total effect of load superposition

From a physical point of view, the simultaneous loadings Y_i (where i = 1,2,3...n) of a mechanical structure determines a total effect X.Generally speaking, the calculation of this effect - is done by superimposing the effects of individual loads Y_i. The method of superposing the effects depends on the behaviour of the mechanical structure material.

For a linear-elastic behaviour of the form

$$Y_i = C \cdot X_i \qquad (1)$$

the total effect is equal to the algebraical sum of the individual effects,

$$X = \sum_{i=1}^{n} X_i. \qquad (2)$$

With nonlinear power law behaviour,

$$Y_i = C \cdot X_i^k, \qquad (3)$$

where *C* and *k* are constants of the material, the total effect is different from the sum of partial effects [4],

$$X \neq \sum_{i=1}^{n} X_i. \qquad (4)$$

In this case, the superposition of effects is done by using the principle of critical energy [1-3].

Effective stresses, critical stresses and the deterioration of cylindrical shells under one single load

Loads Y_i cause stresses σ_i in the crackless shell, whose critical stress, corresponding to a load of the Y_i type is $\sigma_{i,cr}$.

The presence of cracks can be attributed to the effective stress, which in this case is written $\sigma_i(a;c)$or the critical stress which is written $\sigma_{i,cr}(a;c)$ where *a* is the depth of the crack, and 2*c* is the crack length (fig. 1). When analysing the shell strength one compares,

-either $\sigma_i(a;c)$ to $\sigma_{i,cr}$, on condition $\sigma_i(a;c) < \sigma_{i,cr}$;

-either σ_i to $\sigma_{i,cr}(a;c)$, on condition $\sigma_i \le \sigma_{i,cr}(a,c)$.

Our further step was to compare the effective stress σ_i (calculated for the crackless shell) to the critical stress of the cracked shell, $\sigma_{i,cr}(a;c)$

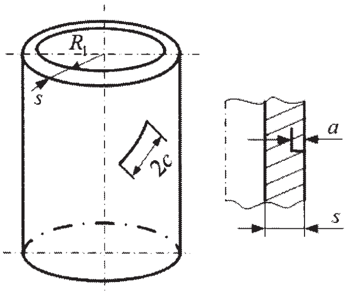

Fig. 1. Cylindrical shell with crack depth a and crack length 2c

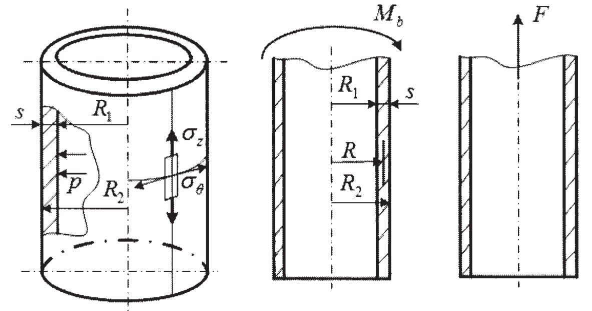

Fig. 2. Cylindrical shell (R_2 / R_1 ≤1.2), under internal pressure p(a) or bending moment M_b(b) or axial force F(c)

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Effective stresses in cylindrical crackless shells under one single static load

One examines the cylindrical shell individually loaded with Y_i = p (internal pressure), F (axial force) or M_b (bending moment) in case the shell material features a linear - elastic behaviour.

In the field of linear-elastic behaviour ($\sigma \leq \sigma_y$ where σ_y is the yield stress), the shell stresses are proportional to the loads. For example, in a cylindrical shell under load:

- under the internal pressure (fig. 2, *a)*, the stresses feature the following expressions[11]:

$$\left.\begin{aligned} &\sigma_z(p)=\frac{p\cdot R}{2s} \text{ - meridional stress;}\\ &\sigma_\theta(p)=\frac{p\cdot R}{s} \text{ - circumferential stress,}\end{aligned}\right\} \qquad (5)$$

where $R=0.5(R_1 + R_2) = R_1 + 0.5s$ is the mean surface ray;

-with axial force *F* (fig. 2, *c*)

$$\sigma_z(F)=\frac{F}{\pi\cdot R\cdot s} \text{ meridional stress} \qquad (6)$$

-with bending moment M_b (fig.2, *b*),

$$\sigma_z(M_b)=\pm\frac{M_b}{4\cdot R^2\cdot s} \text{ meridional stress.} \qquad (7)$$

When under one single load, relations (5) - (7) for effective stresses may be written as:

$$\left.\begin{aligned} &\sigma_z(p)=C_p\cdot p; && \sigma_z(F)=C_F\cdot F;\\ &\sigma_\theta(p)=2C_p\cdot p; && \sigma_z(M_b)=\pm C_M\cdot M_b\end{aligned}\right\} \qquad (8)$$

where C_p, C_F and C_M are constants dependent on the shell geometry.

If stresses become equal to the critical stresses, then relations (8) become,

$$\left.\begin{aligned} &\sigma_{z,cr}(p)=C_p\cdot p_{cr}; && \sigma_{z,cr}(F)=C_F\cdot F_{cr};\\ &\sigma_{\theta,cr}(p)=2\cdot C_p\cdot p_{cr}; && \sigma_{z,cr}(M_b)=\pm C_M\cdot M_{b,cr}\end{aligned}\right\} \qquad (9)$$

where p_{cr}, F_{cr} and $M_{b,cr}$ are the critical values corresponding to crack absence.

By dividing each of the above relations, one obtains:

$$\left.\frac{\sigma_z(p)}{\sigma_{z,cr}(p)}=\frac{p}{p_{cr}}; \qquad \frac{\sigma_\theta(p)}{\sigma_{\theta,cr}(p)}=\frac{p}{p_{cr}};\right\} \qquad (10)$$

$$\left.\frac{\sigma_z(F)}{\sigma_{z,cr}(F)}=\frac{F}{F_{cr}}; \qquad \frac{\sigma_z(M_b)}{\sigma_{z,cr}(M_b)}=\frac{M_b}{M_{bcr}},\right\} \qquad (11)$$

which means that the stress ratios may be replaced by load ratios or viceversa.

Let us consider the general case of the nonlinear behavior of the shell material

$$\sigma = M_\sigma \cdot \varepsilon^k,$$

where σ is the normal stress, ε - strain, M_σ and k - constants of the material.

Critical loads and stresses in cylindrical cracked shells under one single static load

We note the critical loads in the cracked shells $p_{cr}(a;c)$; $F_{cr}(a;c)$ and $M_{b,cr}(a;c)$

On the basis of the critical energy principle, the following relations have been established for the critical loads [6, 9] of mechanical structures with cracks:

$$\left.\begin{aligned} &p_{cr}(a;c)=p_{cr}\cdot[P_{cr}(0)-D(a;c)]^{\frac{1}{\alpha+1}};\\ &F_{cr}(a;c)=F_{cr}\cdot[P_{cr}(0)-D(a;c)]^{\frac{1}{\alpha+1}};\\ &M_{b,cr}(a;c)=M_{b,cr}\cdot[P_{cr}(0)-D(a;c)]^{\frac{1}{\alpha+1}},\end{aligned}\right\} \qquad (12)$$

where $\alpha=1/k$, while D(a;c) is the deterioration caused by a crack with depth *a* and length 2*c*.

$P_{cr}(0)$ is the baseline value of critical participation (t=0) Due to the stochastic distribution of the mechanical characteristics of the structure material $P_{cr}(0)$ takes values between $P_{cr,min}(0) > 0$ and $P_{cr,max}(0) \leq (0)$ 1, which is found when referring to the experimental data. If one uses the deterministic values of the mechanical characteristics (i.e corresponding to a certain probability of fracture), as done in design, $P_{cr}(0)=1$.

For deterioration resulting from cracks one proposed the relation [6; 8],

$$D(a;c)=D(c)\cdot[1+D(a)] \qquad (13)$$

where

$$D(a)=\left(\frac{a}{a_{cr}}\right)^{\frac{\alpha+1}{2}} \text{ and } D(a)=\left(\frac{c}{2c_{cr}}\right)^{\alpha+1}, \qquad (14)$$

where a_{cr} is the critical depth of the crack and $2c_{cr}$ – the critical length of the crack. Deterioration $D(a;c) \in [0;1]$.

Most of the results obtained in the literature for the critical loading of cylindrical shells actually refer to loads before the yield limit. For this reason, the *critical loads* in these cases have been called *yield loads* and written p_L, N_L and $M_{b,L}$. The materials considered in the above mentioned works were elastic-ideally plastic materials (fig. 3), in accordance with Prandtl's hypothesis.

On the basis of relations (11) and (12) we obtain the following general expression of critical stress for cracked mechanical structures

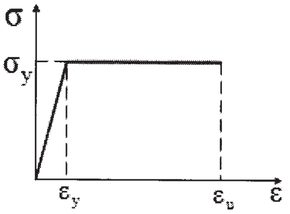


Fig. 3. Diagram of the behaviour of an elastic – ideally plastic material (Prandtl hypothesis) with $\sigma - \sigma_y$ for strains $\varepsilon > \varepsilon_y$

$$\sigma_{cr}(a;c)=\sigma_{cr}\cdot[1-D(a;c)]^{\frac{1}{\alpha+1}}, \qquad (15)$$

where one considered $P_{cr}(0) = 1$ and deterministic values for critical stresses The critical stress σ_{cr} refers to the structure / shell / specimen without cracks.

Crack deterioration caused to a mechanical structure by one single static load

Deterioration occurring under one single load may be calculated by using relations (12) depending on load type,

$$\left.\begin{aligned} &D(a;c)=1-\left(\frac{p_{cr}(a;c)}{p_{cr}}\right)^{\alpha+1};\\ &D(a;c)=1-\left(\frac{F_{cr}(a;c)}{F_{cr}}\right)^{\alpha+1};\\ &D(a;c)=1-\left(\frac{M_{b,cr}(a;c)}{M_{b,cr}}\right)^{\alpha+1},\end{aligned}\right\} \qquad (16)$$

where the critical load values for the crackless structure and cracked structure respectively were determined experimentally.

We may also use equation (15) written for each type of load, as follows,

$$\left.\begin{aligned} D(a;c) &= 1-\left(\frac{\sigma_{p,cr}(a;c)}{\sigma_{p,cr}}\right)^{\alpha+1}; \\ D(a;c) &= 1-\left(\frac{\sigma_{F,cr}(a;c)}{\sigma_{F,cr}}\right)^{\alpha+1}; \\ D(a;c) &= 1-\left(\frac{\sigma_{b,cr}(a;c)}{\sigma_{b,cr}}\right)^{\alpha+1}, \end{aligned}\right\} \qquad (17)$$

where the indices refer to the critical stresses corresponding to loading with pressure (p), axial force (*F)* or bending moment (*b*).

Based on interpreting the literature data via the deterioration relationship (13), one obtained D(a) ∈ [0,1] while D(c) ≤ 0.5 [8;12].

Under the static tensile load with force *F* of tubular steel specimens (fig. 4) with circumferential cracks and rectangular section , one obtained the total deterioration D(a,c) listed in table 1.

Deterioration were calculated with the second relation (16). One should note that the total deterioration increases with reported depths (a/s) increase and with crack lengthening represented by the ratio θ / π.

Deterioration caused in a structure under two simultaneous different loads

Superposition of loads effects

In general, the critical stress depends on the type of load (tensile, compression, bending, torsion, shear ...). For this reason, it may be said that loading with two or more different types of loads represents a complex or a mixed load. Such a load was analyzed and solved for the general case in works [2 -4] on the basis of the principle of critical energy.

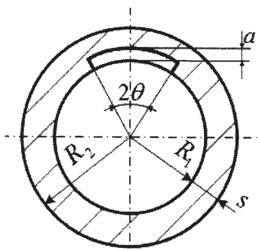


Fig. 4. Section through tube specimen with rectangular circumferential crack on the inner surface

When under two simultaneous loads S_1 and S_2,for structures without residual stress, the critical state is reached when there is fulfilled the condition [3, 4],

$$\left(\frac{S_1}{S_{1,cr}}\right)^{\alpha+1}+\left(\frac{S_2}{S_{2,cr}}\right)^{\alpha+1}=P_{cr}(0)-D(a;c), \qquad (18)$$

wherefrom, the total deterioration caused by the crack becomes,

$$D(a;c)=P_{cr}(0)-\left[\left(\frac{S_{1,cr}(a;c)}{S_{1,cr}}\right)^{\alpha+1}+\left(\frac{S_{2,cr}(a;c)}{S_{2,cr}}\right)^{\alpha+1}\right]. \qquad (19)$$

In case the mechanical characteristics are deterministic variables $P_{cr}(0) = 1$ For structures made from linear elastic materials (k=1), $S_{1cr} = S_{1L}$, $S_{2cr}=S_{2L}$, while $\alpha = 1 / k = 1$, and consequently, deterioration has the following general expression,

$$D(a;c)=1-\left[\left(\frac{S_{1L}(a,c)}{S_{1L}}\right)^2+\left(\frac{S_{2L}(a,c)}{S_{2L}}\right)^2\right], \qquad (20)$$

where $S_{1L}(a,c)$ and $S_{2L}(a,c)$ are the yield stresses of the cracked tubular specimen.

Deterioration of cylindrical shells

The deterioration caused by a crack in the case of the simultaneous action of two loads on the cylindrical shell made from material with *linear-elastic* behaviour, out of the general relation (20) one obtains the following relations:

Table 1

TOTAL DETERIORATION D(A;C) OF TUBULAR SPECIMENS WITH RECTANGULAR CIRCUMFERENTIAL CRACKS UNDER AXIAL FORCE , F, DEPENDING ON a / s AND θ/ π CALCULATED WITH THE SECOND RELATIONSHIP (16)

a/s	θ/π	$\frac{F_{cr}(a;\theta)}{F_{cr}}$, determined from the data reported in the paper [13].	$D(a;c)$, calculated with the second relationship (16)
0.25	0.125	0.983	0.033
	0.25	0.966	0.066
	0.50	0.950	0.097
0.5	0.125	0.966	0.066
	0.25	0.900	0.190
	0.50	0.750	0.437
0.75	0.125	0.900	0.190
	0.25	0.750	0.437
	0.50	0.500	0.750
1.00	0.125	0.816	0.334
	0.25	0.600	0.640
	0.375	0.400	0.840
	0.50	0.200	0.960

- for $S_1 = p$ and $S_2 = M_b$

$$D(a;c) = 1 - \left[\left(\frac{p_L(a;c)}{p_L}\right)^2 + \left(\frac{M_{b,L}(a;c)}{M_{b,L}}\right)^2\right]; \qquad (21)$$

- for $S_1 = p$ and $S_2 = F$ (tensile),

$$D(a;c) = 1 - \left[\left(\frac{p_L(a;c)}{p_L}\right)^2 + \left(\frac{F_L(a;c)}{F_L}\right)^2\right], \qquad (22)$$

- for $S_1 = F$ and $S_2 = M_b$

$$D(a;c) = 1 - \left[\left(\frac{F_L(a;c)}{F_L}\right)^2 + \left(\frac{M_{b,L}(a;c)}{M_{b,L}}\right)^2\right], \qquad (23)$$

where the yield loads of the crackless material (p_{1L}; F_L and $M_{b,L}$) and of the cracked one ($p_L(a;c)$; $F_L(a;c)$ and $M_{b,L}(a;c)$) is determined experimentally.

Calculation of deterioration caused by two load loading

One calculates the deterioration caused in a tubular specimen by two loads (fig. 5 a), based on the results presented in [13]. One considers a cylindrical tube specimen with semi-elliptical circumferential crack on the inner surface (fig. 5, b), based on the relative depth of the crack, *a/s*, and the circumferential length $2c = 2 \cdot R \cdot \theta$ expressed as the ratio θ/π

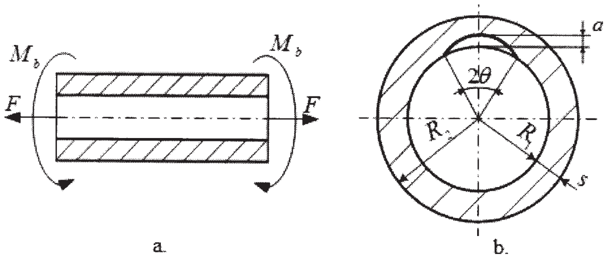
In all the cases presented graphically in [14], the total participation $P_T < 1$, which means that the critical participation $P_{cr}(t) < 1$ due to deterioration.

The total deterioration calculated with relationship (23), where D(a;c) is replaced by D(a,θ) as c~θ. The data reported in [14] refer to two different cracks, characterized by $a/s = 0.1$ and $\theta/\pi = 0.1$ as well as $a/s = 0.3$ and $\theta/\pi = 0.25$, respectively. For each case, the critical state of coordinates $F_L(a;c) / F_L$ - $M_{b,L}(a;c) / M_{b,L}$ is written in the first two columns of table 2. On this basis we calculated the total participation corresponding to the critical state,

$$P_T = \left(\frac{F_{cr}(a;c)}{F_{cr}}\right)^2 + \left(\frac{M_{b,cr}(a;c)}{M_{cr}}\right)^2, \qquad (24)$$

then, with relation (23), one obtained the total deterioration D(a;c) written in table 2.

In the wake of result analysis one has found that for the same crack parameters (a/s and θ/π) there is an infinite number of critical groups, corresponding to all possible combinations among the terms of the load group.



a. b.

Fig. 5. a – Load group comprising axial tensile force, F, and bending moment M_b; b – tube specimen section with circumferential semielliptical crack on the inner surface.

The pressure gradient in the flow of a non- Newtonian fluid

The pressure gradient was calculated by superposing the effects of the Couette driving flow and the Poiseuille pressure flow. One considered a molten polymeric material with non-Newtonian power law behavior (Oswald-de Waele),

$$\tau = K_\tau \cdot \dot{\gamma}^\nu, \qquad (25)$$

where τ is the shear stress; $\dot{\gamma}$ - shear rate; K_τ and ν - constants of the fluid.

The melt moves under pressure in a channel with a fixed wall and another one moving at speed V_z in the direction of flow (fig. 6). The final speed profile is obtained through the superposition of the two speed profiles shown in figure 6a and 6b.

If the pressure acts in the same direction as speed V_z, then the two speed profiles add up (fig. 6*c*), whereas if the pressure acts in the direction opposite to V_z, the two speed profiles are subtracted from one another (fig. 6*d*).

Let us write for the maximum flow corresponding to the superposition of the two actions (V_z and p).

By superposing the effects of the two flows, based on the principle of critical energy, one obtained the following relation for the pressure gradient at a given distance *z* along the flow path [5;15],

$$\frac{dp}{dz} = \left[1 - \left(\frac{V_Z}{V_{Z,cr}}\right)^{1+\nu}\right]^{\frac{\nu}{\nu+1}} \cdot \left(\frac{dp}{dZ}\right)_{cr} \cdot \delta_p, \qquad (26)$$

where $V_{Z,cr}$ is the critical driving speed, that is, the speed of the plate movement which alone provides the same flow rate G_m, and $(dp / dZ)_{cr}$ is the critical pressure gradient, that is that pressure gradient which alone supplies flow rate G_m.

Factor $\delta_p = 1$ if the pressure increases in the direction of movement and $\delta_p = -1$, if the pressure drops in the direction of movement.

a/s	θ/π	$\frac{F_L(a;c)}{F_L}$	$\frac{M_L(a;c)}{M_L}$	P_T	D(a;c), calculated with relationship (23)
0.1	0.1	0.400	0.7868	0.7790	0.2210
		0.6134	0.5912	0.7257	0.2743
		0.7564	0.3737	0.7125	0.2875
0.3	0.25	0.400	0.800	0.800	0.200
		0.600	0.600	0.720	0.280
		0.750	0.374	0.7023	0.2977

Table 2
DETERIORATION D(a;c) OF TUBULAR SPECIMENS WITH CIRCUMFERENTIAL CRACK ON THE INNER SURFACE

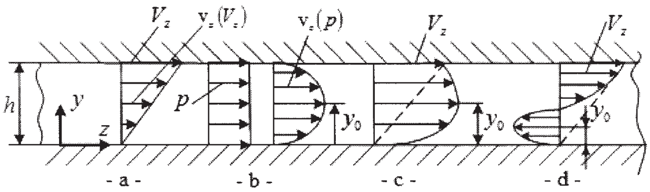


Fig. 6. The velocity profile with flow between two parallel plates due to: a - melt being driven by top plate moving at speed V_z (Couette flow); b - pressure p in the direction of flow (Poiseuille flow); c - pressure acting in the same direction with plate speed; d - pressure acting in the opposite direction to plate speed

For example, when a polymer melt flows through an extruder screw channel, the pressure increases in the area preceeding the maximum pressure section (L_{PM}) and decreases thereafter (fig. 7). Exponents $1/\nu + 1$, $1/\nu + 3$, etc. are even numbers [16] so that the large brackets in equation (26) is always a positive number.

When a molten polyethylene moves through an extruder screw channel featuring D = 63.5mm in diameter and three geometrical zones, one recorded the evolution of pressure along the screw axis of length L = 27 . D [17] whose maximum pressure p_M = 27.8 MPa was reached at distance L_{PM} = 21D = 1333.5 mm. Pressure at L_1 = 5D = 317.5 mm was p_1=0.1 MPa . The experimental pressure gradient.

$$\left(\frac{dp}{dZ}\right)_{\exp} \approx \frac{27.8-0.1}{1333.5-0.3175} = 27.2\ \mathrm{MPa/m}$$

By using relation (26) one obtained [15],

$$\frac{dp}{dz} = \left[1-\left(\frac{V_Z}{V_{Z,cr}}\right)^{1+\nu}\right]^{\frac{\nu}{\nu+1}} \cdot \left(\frac{dp}{dZ}\right)_{cr} \cdot$$

$$\cdot \delta_p = \left[1-\left(\frac{0.26423}{0.23103}\right)^{1+0.345}\right]^{\frac{0.345}{1+0.345}} \cdot (54.943) \cdot 1 = 28.135\ \mathrm{MPa/m},$$

where, according to the calculaitons in [15], V_Z = 0.26423 m/s, while the mass flow rate G_m = 100.72 kg/h, one obtained $V_{Z,cr}$ = 0.23103 m/s and $(dp/dZ)_{cr}$ = 54.934 MPa/ m. One set δ_p = 1 as the calculation refers to the zone where the pressure increases, before its maximum pressure position L_{PM} (fig. 7).

The difference between the value calculated with equation (26) obtained on the basis of the critical energy principle and the resulting experimental value is 3.44%, which is insignificant for such flows.

Conclusions

One examined the problem of superposition effects with: - two loads acting simultaneously on a tubular element with cracks; - the combination of driving flow and pressure flow of a non-Newtonian fluid. We dealt with the general case of nonlinear power law behaviour. Relations were proposed for calculating critical loads (12), and critical stresses (15) in cylindrical shells under one single static load, by taking into consideration the deterioration caused by the crack. Relationships were also proposed for calculating shell deterioration based on experimental data ((16) and (17)), by considering both crack depth and length. One highlighted the influence of stochastic dispersion of the mechanical characteristics of the experimental results by introducing the concept of critical participation, $P_{cr}(0)$, at moment t = 0.

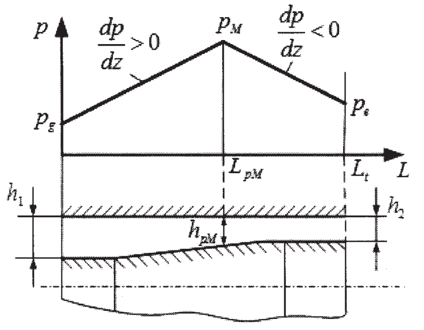


Fig. 7. Evolution of pressure along the screw channel provided with a compression zone located between the flat zones with depths h_1 and h_2

It is against this backdrop that there have been proposed relations for calculating the deterioration caused by a group of loads in the case of non-linear material behavior ((21) - (23)).

The relations obtained were used in calculating deterioration of cylindrical tube specimens loaded by axial force and bending moment.

The relations obtained are recommended for the calculation of critical stresses (such as fracture) and critical load groups, under static loading of mechanical structures with cracks by considering the statistic distribution of the mechanical characteristics of the structure material.

In the second part of the paper one applied the principle of critical energy to the superposition of the effects of driving (Couette) flow and pressure (Poiseuille) flow of a Non-Newtonian fluid. The expression obtained for the pressure gradient (26) thoroughly matched the experimental data.

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